NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2569

A SUMMARY OF METEOROLOGICAL CONDITIONS ASSOCIATED WITH AIRCRAFT ICING AND A PROPOSED METHOD OF SELECTING DESIGN CRITERIONS FOR ICE-PROTECTION EQUIPMENT

By Paul T. Hacker and Robert G. Dorsch

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

Data from various sources on the observed values of meteorological variables, liquid-water content, mean-effective droplet size, and temperature, which are pertinent to aircraft icing, are summarized; and a method is proposed for the selection of design criterions for ice-protection equipment.

The data are divided according to two broad cloud types, namely, stratiform and cumuliform clouds, because the physical dimensions, the formation and development processes, the frequency of encounter, and the severity of icing conditions are very different for the two cloud types. The data are summarized in such a manner as to give the frequency of occurrence of observed icing conditions according to two of the pertinent meteorological variables. The summarized data indicate that statistical relations exist between liquid-water content, mean-effective droplet diameter, temperature, and pressure altitude.

The proposed method of selecting values of liquid-water content and mean-effective droplet diameter as design criterions for ice-protection equipment is based upon the collection efficiency of an airfoil as a function of droplet size and the frequency of occurrence of icing situations with various liquid-water contents and mean-effective droplet diameters. The method provides a convenient means of calculating the percentage of icing encounters in which the water-collection rate exceeds the design rate for the ice-protection equipment and also illustrates the desirability of sometimes designing ice-protection equipment for water-collection rates which are less than the maximum rate expected. The method is illustrated by the selection of design criterions for ice-protection equipment for a hypothetical, 12-percent thick, low-drag airfoil with a chord length of 15.8 feet; however, the method may be employed for any airfoil provided the collection efficiency is known.

INTRODUCTION

For several years research has been conducted on the prevention and removal of ice formations caused by supercooled clouds on components of aircraft by the addition of heat to the vulnerable components. In order to evaluate the heat requirements of an ice-prevention system that provides adequate protection against icing caused by supercooled clouds, 2279 the rate at which supercooled liquid cloud droplets are collected by each portion of the surface of the airplane, the probable maximum duration, and the frequency of occurrence of various icing conditions must be known. The evaluation of these unknowns requires the following information about supercooled clouds: (1) liquid-water content, (2) droplet diameter and droplet-size distribution, (3) air temperature and pressure, (4) horizontal and vertical extent of icing situations, and (5) frequency of occurrence of icing conditions of a given description.

Incomplete information concerning the fundamental physical processes that determine the structure of clouds and cloud systems has necessitated an experimental and statistical approach to the definition of the important features of an icing cloud. Flights have been made by the NACA and other agencies with instrumented aircraft through supercooled clouds for the past several years in order to establish, for the pertinent meteorological variables, the range of values encountered in icing conditions. As a result of these instrumented flights, a considerable accumulation of meteorological data pertinent to the icing problem has been obtained and published.

As part of the NACA Lewis laboratory icing-research program, this report summarizes the existing meteorological data from various sources and proposes a method of selecting design criterions for ice-protection equipment. The data are summarized in such a manner as to give the frequency of occurrence of icing situations with a given combination of two of the principal meteorological variables. These frequencies of occurrence are used in combination with water-collection rates for an aircraft component as a basis for the proposed method of selecting design criterions for ice-protection equipment. This method gives a convenient means of determining the percentage of icing encounters in which the water-collection rate exceeds the collection rate for which the ice-protection system is designed. The method is illustrated by the selection of design criterions for ice-protection equipment for a hypothetical, 12-percent thick, low-drag airfoil with a chord length of 15.8 feet.

SUMMARY OF MEASURED ICING PARAMETERS

Sources of Data

The icing-parameter measurements summarized in this report have been previously published: those on liquid-water content, mean-effective droplet diameter, ambient air temperature, and pressure altitude of icing conditions in references 1 to 4; those on horizontal and vertical extent of icing situations in references 4 to 6. Although more data have been collected, only those that can be directly compared and summarized have been included. These data, with the exception of those in reference 6, have been collected by the NACA with instrumented aircraft.

The aircraft instrumentation used consisted of all or part of the following instruments: (1) airspeed indicator and recorder; (2) altimeter and altitude recorder; (3) thermocouple or resistance-bulb thermometer shielded from radiation and direct impact of water for measurement of free-air temperature; (4) rotating multicylinders for the determination of liquid-water content, mean-effective droplet diameter[1], droplet-size distribution, and extent of icing conditions; (5) cloud indicator for the determination of extent of cloud or icing condition; (6) fixed cylinder for the determination of maximum droplet diameter; and (7) rotating-disk icing-rate meter for the determination of the spatial extent of icing conditions and maximum liquid-water content over short intervals. Most of these instruments are recognized as standard ice-research equipment and they are adequately described in the literature (references 1, 2, 5, 7, and 8).

Method of Summarizing Data

The data on liquid-water content, mean-effective droplet diameter, ambient air temperature, and pressure altitude of icing conditions are divided into two categories: for stratiform and cumuliform clouds. Stratiform clouds are layer-type clouds in which the horizontal extent is much greater than the vertical thickness. This cloud type includes stratus, strato-cumulus, alto-stratus, alto-cumulus, and nimbo-stratus. Cumuliform clouds are clouds with vertical extent comparable to the horizontal extent. This cloud type includes cumulus, cumulus congestus, cumulo-nimbus, and alto-cumulus-castellatus. This division of icing situations was necessary because the icing conditions in the two cloud types are very different, owing to the difference in the manner in which

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[1]The mean-effective droplet diameter is a volume median droplet size, that is, the amount of water in all droplets of diameter greater than the mean-effective diameter is equal to the amount of water in all droplets of smaller diameter.

they are formed. In addition, the frequency of encounter of icing conditions in stratiform clouds by an aircraft in routine flight is much greater than in cumuliform clouds. The percentage of all icing encounters in routine flight that occur in cumuliform clouds is 5 percent according to reference 9.

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The meteorological data on liquid-water content, mean-effective droplet diameter, ambient air temperature, and pressure altitude of icing conditions are summarized in the form of bivariate frequency-distribution charts in order to show the frequency of occurrence of icing conditions according to two of the variables and the statistical relation between these two variables. The importance of the frequency of occurrence of a given icing condition in the selection of values of the meteorological variables as design criterions for ice-protection equipment is illustrated by the proposed method of selecting design criterions. The statistical relations between liquid-water content and pressure altitude, mean-effective droplet diameter and pressure altitude, and temperature and pressure altitude are useful in estimating probable icing conditions at altitudes above 20,000 feet where observed data are lacking. In addition, these statistical relations are of interest to aeronautical meteorologists and flight crews as well as designers of ice-protection equipment for airplanes.

Sufficient data on horizontal and vertical extent of icing conditions have not been collected to date to permit the presentation of the data in such a form as to give the frequency of occurrence of various icing conditions as a function of extent of condition. However, the extent of icing conditions is of fundamental importance to designers of ice-protection equipment and therefore the limited data have been included in this summary.

Liquid-Water Content as Function of Pressure Altitude

The liquid-water content of an icing condition may be regarded as the most important icing parameter because it determines the maximum possible rate of ice accumulation on an airfoil. In general, however, the rate of ice accumulation on an airfoil moving through a supercooled cloud is considerably less than this maximum because some of the water droplets are deflected around the airfoil.

The liquid-water content of stratiform and cumuliform clouds as a function of pressure altitude is summarized in figures 1(a) and 1(b), respectively, in the form of bivariate frequency-distribution charts. These charts indicate the frequency of occurrence of icing conditions for various increments of liquid-water content and pressure altitude. For example, in stratiform clouds between pressure altitudes of 4000 and 6000 feet, 24 icing conditions were observed with liquid-water contents between 0.36 and 0.48 gram per cubic meter. Curves of maximum and average values of liquid-water content as functions of pressure altitude are also shown in the figures.

The average liquid-water content for both cloud types in general increases with altitude to a maximum value then decreases with further increase of altitude. The maximum values of average liquid-water contents, however, do not occur at the same pressure altitude for both cloud types. The maximum value of average liquid-water content for stratiform clouds occurs at 5000 feet as compared with 13,000 feet for cumuliform clouds. For any given altitude the average liquid-water content of cumuliform clouds is higher than for stratiform.

2279 The range of liquid-water content for a given altitude as indicated by the maximum curves (fig. 1(a) and 1(b)) is different for the two cloud types. The largest range of liquid-water content, 0 to 0.96 gram per cubic meter, for stratiform clouds occurs in the pressure-altitude range of 4000 to 8000 feet, whereas in cumuliform clouds the largest range, 0 to 1.68 grams per cubic meter, occurs in the pressure-altitude range of 14,000 to 16,000 feet. Although the range of liquid-water content is large, the frequency of occurrence of icing situations with high liquid-water content is small compared with the total number of icing encounters; for example, only five out of 158 observations in stratiform clouds (fig. 1(a)) have liquid-water contents greater than 0.60 gram per cubic meter.

These data indicate that a statistical relation exists between liquid-water content and pressure altitude; however, the relation is different for the two cloud types. On the basis of liquid-water content alone the severity of icing conditions would in general be greater in cumuliform than in stratiform clouds, because the average values and the range of liquid-water contents are greater in cumuliform clouds.

Cloud Droplet Diameter as Function of Pressure Altitude

A component or an airfoil of an aircraft in flight through a cloud usually does not intercept all the droplets in its path, because some of the droplets are deflected around the airfoil by the air flow. The percentage of droplets intercepted depends on, among other factors, the droplet size and increases with increasing droplet size if all other factors are constant. Because the percentage catch, and therefore the rate of ice accumulation, are functions of droplet size, any relation between droplet size and pressure altitude is of importance, for possibly the altitude of severest aircraft icing would not coincide with the altitude of maximum liquid-water content indicated by figure 1.

Data collected during icing survey flights indicate that cloud droplets in a given icing situation are not always uniform in size but may be distributed over a wide range of sizes. Because the droplet-size distribution may influence the rate of ice accumulation on various areas of an airfoil, it should be employed in the design calculations for ice-protection equipment. The introduction of this factor, however, greatly complicates the design calculations; therefore it has not been used extensively. The mean-effective droplet diameter has been employed instead. Furthermore, some doubt exists as to the validity of the droplet-size distribution measurements.

Bivariate frequency-distribution charts of mean-effective droplet diameter as a function of pressure altitude for icing conditions in stratiform and cumuliform clouds with curves of maximum and average values of mean-effective droplet diameter are presented in figures 2(a) and 2(b). If the one observation in the altitude range 0 to 2000 feet in stratiform clouds (fig. 2(a)) is regarded as insufficient data for average-mean-effective-droplet-diameter calculations, then the average and maximum values of mean-effective droplet diameter are very similar for the two cloud types. The average value of mean-effective droplet diameter for any given altitude for cumuliform clouds is in general from 1 to 4 microns larger than for stratiform clouds. For both cloud types the over-all average mean-effective droplet diameter is higher in the pressure-altitude range of 10,000 to 20,000 feet than in the range of 0 to 10,000 feet. 2279

Although a large range of droplet diameter is indicated, the frequency of occurrence of icing situations with extremely large mean-effective droplet diameters is very low compared with the total number of observations.

From the foregoing analysis there appears to be a statistical relation between mean-effective droplet diameter and pressure altitude, which is about the same for the two cloud types. A comparison of figures 1 and 2 shows that the pressure-altitude range of highest liquid-water content in stratiform clouds is below the pressure-altitude range of largest mean-effective droplet diameter, whereas in cumuliform clouds the two ranges nearly coincide.

Liquid-Water Content as Function of Mean-Effective Droplet Diameter

The frequency of occurrence of icing situations with various combinations of liquid-water content and mean-effective droplet diameter is of importance because the rate of ice accumulation on an aircraft component depends on both the liquid-water content and mean-effective droplet diameter. Bivariate frequency-distribution charts of these two variables are presented in figure 3. The data are divided into four categories: (1) stratiform clouds in the pressure-altitude range of 0 to 10,000 feet (fig. 3(a)), (2) cumuliform clouds in the pressure-altitude range of 0 to 10,000 feet (fig. 3(b)), (3) stratiform clouds in the pressure-altitude range of 10,000 to 20,000 feet (fig. 3(c)), and (4) cumuliform clouds in the pressure altitude range of 10,000 to

20,000 feet (fig. 3(d)). The data are divided into the two altitude ranges because the rate of ice collection is, to a slight degree, dependent on temperature and pressure. These summaries are used in a later section of this report to illustrate the proposed method of selecting design criterions for ice-protection equipment.

The most probable icing condition on the basis of liquid-water content and mean-effective droplet diameter for the four categories of figure 3 is indicated by the maximum frequency of occurrence of observations. The most probable icing condition for stratiform clouds is approximately 0.19 gram per cubic meter and 12 microns for the pressure-altitude range of 0 to 10,000 feet, whereas the most probable icing condition for cumuliform clouds in the same altitude range is approximately 0.42 gram per cubic meter and 21 microns. In the pressure-altitude range of 10,000 to 20,000 feet the most probable icing condition for stratiform clouds is approximately 0.06 gram per cubic meter and 15 microns. The most probable icing condition for cumuliform in this altitude range is not as well defined as for the other categories, but it appears to be approximately 0.18 gram per cubic meter and 20 microns.

Also presented in figure 3 are average values of liquid-water contents for various increments of mean-effective droplet diameters and average values of mean-effective droplet diameter for various increments of liquid-water content. These average values are indicated by the numbers at the top and right side of the figure.

The average liquid-water-content conditions for the four categories (figs. 3(a) to 3(d)) can be summarized as follows: (1) the average liquid-water content for a given mean-effective-droplet-diameter increment is usually higher for cumuliform than for stratiform clouds; (2) the average liquid-water content of stratiform clouds for a given mean-effective-droplet-diameter increment is higher for clouds in the 0- to 10,000-foot range than in the 10,000- to 20,000-foot range; for cumuliform clouds, conditions are opposite, that is, the average liquid-water content is greater at the high altitudes.

The average mean-effective-droplet-diameter conditions for the four categories (figs. 3(a) to 3(d)) can be summarized as follows: (1) the average mean-effective droplet diameter for a given liquid-water-content increment is usually about 5 microns larger in cumuliform than stratiform clouds for both altitude ranges; (2) the average mean-effective droplet diameter for a given liquid-water-content increment is larger for stratiform clouds and, in general, is slightly larger for cumuliform clouds in the 10,000- to 20,000-foot range than in the 0- to 10,000-foot range.

The foregoing analysis indicates a statistical relation between liquid-water content and mean-effective droplet diameter. Therefore, when selecting values of these parameters as design criterions for ice-protection equipment, caution should be exercised, because individual values of the parameters could be selected that, when considered alone, appear to be reasonable, but would occur very seldom in combination in an icing situation. The method proposed in later sections of this report for the selection of design criterions is based upon the data summarized in figure 3; therefore the values of mean-effective droplet diameter and liquid-water content used in the illustrative example are consistent with atmospheric conditions in icing situations.

Temperature of Icing Clouds as Function of Pressure Altitude

The ambient air temperature of an icing situation must be considered in the design of ice-protection equipment because the cloud-droplet impingement on an airfoil is a function of air viscosity and density. Moreover, the temperature of an icing condition is important in the calculation of the amount of heat required to maintain the surface of an airfoil at a temperature above freezing in order to prevent or remove ice formation.

Bivariate frequency-distribution charts of temperatures of icing situations as a function of pressure altitude for stratiform and cumuliform clouds are presented in figures 4(a) and 4(b), respectively. Also indicated on the charts are curves of average temperatures of icing conditions and standard-atmosphere temperatures as a function of pressure altitude.

A comparison of the two charts shows that the range of temperatures encountered in stratiform clouds (fig. 4(a)) is much greater than for cumuliform clouds (fig. 4(b)) at low pressure altitudes, but is very similar at pressure altitudes above 8000 feet. The average temperature at pressure altitudes below 7000 feet is slightly lower for stratiform clouds than for cumuliform clouds, but from 7000 to 21,000 feet is generally higher for stratiform than for cumuliform clouds. For low pressure altitudes the average temperatures for both cloud types are lower than for the corresponding temperatures of the NACA standard atmosphere, whereas for higher pressure altitudes the average temperatures are slightly higher.

Extent of Icing Condition

Although data on horizontal and vertical extent of icing conditions are limited, sufficient data have been obtained to indicate the order of magnitude of these icing variables.

The maximum horizontal extent of icing situations with a given average liquid-water content is presented in figure 5. The dashed curve is an estimate of the probable maximum horizontal extent of winter icing situations with a given average liquid-water content as proposed in reference 5. The solid curve is an envelope of the maximum distance flown in icing conditions with a given average liquid-water content, as measured and reported by reference 4, for 57 flights in icing conditions during four winter icing seasons from 1946 to 1950. The curves of figure 5 are similar and show an inverse relation between average liquid-water content and maximum horizontal extent of icing situations. The majority of observations on which the estimated curve is based were taken in cumuliform clouds, whereas a large majority of observations on which the measured curve is based were in stratiform clouds. This difference probably accounts for the higher liquid-water content indicated for short distances by the estimated curve, as the liquid-water content is usually higher in cumuliform clouds than stratiform clouds.

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The maximum vertical extent of icing conditions observed in stratiform clouds as reported by reference 4 was approximately 6500 feet. This icing condition consisted of multiple cloud layers, and the layers were sufficiently close together with varying tops and bases that icing conditions were unavoidable without frequent changes of flight path. According to reference 4, 89 percent of icing conditions observed in stratiform clouds were less than 5000 feet in vertical extent.

The maximum vertical extent of icing conditions observed in cumuliform clouds as reported in reference 6 for 33 observations was approximately 9000 feet with approximately 80 percent of the observations at less than 6000 feet. Although these observations are limited in number and were taken over a period of only 6 months, they are sufficient to indicate that the vertical extent of icing conditions may be greater for cumuliform than for stratiform clouds.

Limitations of Summarized Data

The rotating-multicylinder method of determining liquid-water content and mean-effective droplet diameter of icing conditions depends basically on the amount of ice collected on cylinders of various sizes; therefore, the method gives data which can be adapted for the design of ice-protection equipment for various components of an airplane, because the errors due to losses by droplet blow-off, bounce-off, and evaporation should be comparable for cylinders and various airplane components. From a purely meteorological point of view, however, the measured values of these parameters may be in error because of these losses. In addition, there is a certain amount of subjective error in the evaluation of liquid-water content and mean-effective droplet diameter because the measured amount of ice collected on cylinders of various sizes have to be matched with theoretical amounts calculated on the basis of droplet trajectories for cylinders (reference 8). The correlation between the actual amounts of ice collected and the theoretical values is usually imperfect because the theoretical values are based upon hypothetical droplet-size distributions which do not necessarily exist in an icing situation; therefore the data on liquid-water content and mean-effective droplet diameter depend to some extent on the judgement of the analyst.

Because of these possible errors, caution should be exercised in the use of the data summarized in figures 1 to 4 for verification of theoretical considerations of cloud formation and structure until the errors are evaluated by measurements of liquid-water content and droplet size by independent methods. Although these data may be subject to question for determining the fundamental physical properties of cloud structures and development processes, they can be of use to aeronautical meteorologists as an aid in forecasting the occurrence and the severity of icing situations. 2279

The pressure altitudes of icing conditions given in figures 1, 2, and 4 are in terms of the NACA standard atmosphere. This procedure yields data that may be compared at a given pressure but does not give the actual height above sea-level or the underlying terrain. The actual height above the terrain would be of considerable importance in theoretical considerations of cloud formation and structure. However, the pressure altitude is of importance because the design criterions for ice-protection equipment are implicit functions of the ambient pressure of icing situations.

Further limitations of the data summarized in figures 1 to 4 are: (1) A very large majority was obtained during the winter and spring months of the year, (2) most of the research flights on which the data were obtained have been restricted to the Great Lakes and West Coast regions of the United States, and (3) a large percentage of the data for pressure altitudes above 10,000 feet was obtained in the West Coast region of the United States. Because of these limitations any design criterions for ice-protection equipment based upon these data cannot be accepted as universal until further flight measurements have been made.

Although these data have limitations, it will be necessary to assume in this report that they are sufficient to give reliable indications of average and maximum icing conditions, as well as frequency of occurrence of specified icing conditions, in order to determine tentative design criterions for ice-protection equipment for aircraft.

SELECTION OF METEOROLOGICAL FACTORS FOR ICE-PROTECTION-SYSTEM DESIGN

Because the amount of heat required by ice-protection systems of high-speed jet aircraft to evaporate all the intercepted supercooled water from the vulnerable components is often very large, it may be necessary to design ice-protection equipment for some components for icing conditions of less severity than the maximum expected in order to keep the heat requirements to acceptable values. This may be particularly necessary if the probability of encountering the severest icing condition is very low and the heat required for protection for this situation is several times that required for the most probable icing condition.

This approach to ice-protection equipment design may be feasible, because severe icing situations are usually those with high liquid-water content and therefore generally of short horizontal extent (fig. 5); and some components with high heat requirements, such as wings, can often tolerate small accumulations of ice for short periods of time without excessive airplane performance losses. Data obtained during the recent Thunderstorm Project (reference 10) on icing conditions in cumuliform clouds is of interest in this connection. A total of 305 traverses of cumuliform clouds by P-61C airplanes were made in icing conditions, and on no occasion did ice accumulate before the end of a traverse to such an extent as to make safe flight impossible. Inasmuch as these flights were made with relatively slow airplanes with reciprocating engines, no direct conclusions can be drawn from these flights regarding safety of flight through cumuliform clouds with high liquid-water content by jet-powered aircraft other than that it may be possible to fly in icing conditions which will overload the ice-protection system for short periods of time without loss of control before emerging into clear air or less severe icing conditions. For jet-powered aircraft with thin high-speed wings, the amount of ice that can be tolerated may be considerably less than that for low-speed wings. In addition, critical components such as turbine-engine inlets must be kept ice free at all times; and ice-protection equipment for these components must be designed to cope with the maximum icing conditions anticipated. In general, these critical areas do not require a large percentage of the total heat requirements.

If this approach to ice-protection-equipment design is employed, it is desirable to know the probability of encountering an icing situation of a given severity and the severest condition that may be encountered. The heat required by an airplane component is a function of the airspeed, atmospheric pressure, distribution of intercepted water over the surface of the component, air temperature, and rate of water interception. Therefore an ice-protection system may be inadequate if any of the variables exceed the value for which the system was designed. For a complete evaluation of the probability of encountering an icing situation of a given severity, all these variables should be considered simultaneously. Because of its complexity and the incompleteness of the meteorological data available at the present time, a complete solution will not be attempted. However, an approximate evaluation of the probability of encountering an icing situation of a given severity for a given component and flight condition can be obtained by considering the rate of water interception and the data presented in figure 3. This approximation is possible because the heat required by a component to evaporate the intercepted water for the range of temperatures and pressures encountered in icing conditions depends largely on the amount of water collected. 2279

In order to evaluate the rate of water interception by a component, the collection efficiency of the component must be known. The collection efficiency of an airfoil, defined as the ratio of the water intercepted by the component to the total mass of water in the volume swept out by the moving airfoil at zero geometric angle of attack, is a function of the physical dimensions of the airfoil, the airspeed, and the angle of attack as well as the meteorological variables: droplet size, air temperature, and pressure. The air temperature and pressure enter into the relation indirectly as parameters determining the viscosity and density of the air. The collection efficiency of an airfoil can be obtained from droplet trajectory calculations such as those presented in reference 11.

This approach to the design of ice-protection equipment can best be presented by means of an example. Assume that the probability of encountering an icing situation with a given rate of water interception is desired for a hypothetical, 12-percent thick, low-drag airfoil with a chord length of 15.8 feet for a climb condition from 0 to 20,000 feet at 350 miles per hour. Estimates of the collection efficiency as a function of droplet size for such a hypothetical airfoil for two operating and meteorological conditions are presented in figure 6. The temperatures, 20° F and 0° F, associated with the two collection-efficiency curves for pressure altitudes of 5000 and 15,000 feet, respectively, were obtained from the data presented in figure 4 and are approximately the mean temperatures measured in icing conditions for the altitude ranges of 0 to 10,000 feet and 10,000 to 20,000 feet, respectively, as well as the mean temperatures for the two pressure altitudes of 5000 and 15,000 feet. The angle of attack was increased from 1.5° at 5000 feet to 2° at 15,000 feet in order to maintain the airspeed constant at 350 miles per hour during climb. Since the collection efficiency of the airfoil does not change much in going from 5000 to 15,000 feet, it is assumed that the curve for 5000 feet is representative of the collection efficiency of the airfoil in the pressure altitude range of 0 to 10,000 feet and the curve for 15,000 feet is representative for the pressure altitude range of 10,000 to 20,000 feet.

When these relations between collection efficiency and droplet size are combined with the equation for the rate of water interception, curves of constant rate of water interception as functions of liquid-water content and droplet size are obtained. The rate of water interception is given by the following equation:

$$M_T = 0.3296\ E_M VmtC$$

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where

M_T mass of water intercepted, pounds per hour per foot of airfoil span

0.3296 conversion factor

E_M collection efficiency of airfoil, percent

V airspeed, miles per hour

m liquid-water content, grams per cubic meter

t airfoil thickness, percent of chord length

C chord length, feet

Curves of constant water-collection rates as functions of liquid-water content and droplet size for the two pressure-altitude ranges of the two cloud types are shown in figure 7. These curves are superimposed upon the data of figure 3. The percentage of icing encounters with water-collection rates less than a given value for a given cloud type and pressure-altitude range is given by the ratio of the sum of the icing encounters in the region below and to the left of a given water-collection-rate curve to the total number of icing encounters for the given cloud type and pressure-altitude range.

Cumulative frequency curves of the percentage of icing encounters with rates of water collection less than a given value for the four cloud classifications of figure 7 obtained in the preceding manner are presented in figure 8. The water-collection rate increases very rapidly above 90 percent of all encounters. It may therefore be desirable to exploit the tolerance of various components to small quantities of ice accumulations and the small frequency of occurrence of severe icing conditions in order to keep the heat requirements to acceptable values. A comparison of the cumulative frequency curves for stratiform clouds (figs. 8(a) and 8(c)) with those for cumuliform clouds (figs. 8(b) and 8(d)) shows that an ice-protection system designed for a given water-collection rate will provide a much higher percentage of protection for flights in icing conditions in stratiform clouds than in cumuliform clouds. However, if only 5 percent of all icing encounters during routine flight operation occur in cumuliform clouds (reference 9), then the probability of encountering an icing situation during routine flight with a water-collection rate higher than the design rate is only slightly higher than that calculated for icing encounters for stratiform clouds alone.

Even when the other variables which determine heat requirements 2279
are neglected, a constant water-collection rate does not imply a constant heat requirement to evaporate the water, because the quantity of heat varies with the local distribution of the intercepted water over the surface of the airfoil. This local distribution is a function of droplet size. However, for an appreciable portion of a constant water-collection-rate curve the effect of changing droplet size on the heat required to evaporate the intercepted water may often be relatively small. Therefore, this method provides at least a reasonable estimate of the probability of encountering an icing situation too severe for the ice-protection equipment.

By this method a rate of water collection can be selected as the design criterion for ice protection for a particular component. The particular water-collection rate selected will depend on the degree of protection required by the component. Since the collection efficiency of a component depends on its physical dimensions, the water-collection rates for various components will not necessarily be the same for a given meteorological condition. Therefore, it will be necessary to apply the above procedure of selecting design criterions to all components, if the total heat requirement for adequate and efficient ice protection for a high-speed aircraft is to be held to a minimum.

This method of selecting design criterions eliminates the difficult problem of selecting from the meteorological data on liquid-water content and droplet size (figs. 1 to 3) a specific combination of these two variables to be used as design criterions for ice-protection equipment for all components of an aircraft. The problem is difficult because the water-collection rates for various components and combinations of liquid-water content and droplet size are very different, and also the degree of protection required for various components is different. Therefore, ice-protection equipment designed for a specific combination of liquid-water content and droplet size may provide adequate protection for some components for all possible combinations of liquid-water content and droplet size. However, for other components and combinations of liquid-water content and droplet size the heat requirements calculated on the basis of a specific combination of liquid-water content and droplet size may be too low or too high, thereby resulting in an ice-protection system that would be inadequate or inefficient.

Although a specific combination of liquid-water content and droplet size is not obtained by this method, it is often necessary to select a representative value of mean-effective droplet size, and assume or determine from data presented in references 1 to 4 a representative value of droplet-size distribution in order to determine representative values of chordwise extent of droplet impingement and the local distribution of the intercepted water. These factors have to be evaluated in order to determine the local distribution of the heat requirements and the chordwise extent of the heated area. In practice, however, it is usually necessary to extend the chordwise heated distance beyond the impingement zone because of possible runback before evaporation is complete and the high airfoil surface temperatures required to evaporate the intercepted water within the impingement zone. Therefore, the selection of a representative mean-effective droplet diameter is not too critical and may be obtained from the data presented in figure 7. Usually this representative mean-effective droplet diameter will be a value intermediate between the most probable and the maximum mean-effective droplet diameter to be expected for the cloud type and altitude range in which the airplane will operate.

Although this method of determining design criterions is especially adaptable for ice-protection equipment of the continuous heating type that evaporates the intercepted water, some of the concepts involved may be of considerable use in selecting design criterions for other types of ice protection. This will be especially true when more complete information is available on the frequency of occurrence of icing conditions with specific combinations of liquid-water content, droplet size, air temperature, air pressure, and extent of icing, and when information is also available on droplet trajectory calculations for various aircraft components.

CONCLUDING REMARKS

Data on the range of values of the meteorological variables pertinent to the aircraft icing problem have been summarized and a method has been proposed for the selection of design criterions for ice-protection equipment of the continuous heat type that evaporates the intercepted water. The summarized data indicate that statistical relations exist between liquid-water content, mean-effective droplet diameter, temperature, and pressure altitude. Therefore, when selecting values of these parameters as design values, caution should be exercised because individual values of these parameters could be selected that, when considered alone, appear to be reasonable, but would occur very seldom in combination in an icing situation. The proposed method of selecting design criterions is based upon the collection efficiency of the airfoil as a function of droplet size and the frequency of occurrence of icing situations with various liquid-water contents and mean-effective droplet sizes. The method provides a convenient means of

calculating the percentage of icing encounters in which the ice-collection rate exceeds the design rate for the ice-protection equipment. The method also illustrates the desirability of exploiting the tolerance of various components to small quantities of ice accumulations, because the frequency of encounter of icing situations with extremely high ice-collection rates is low. Ice-protection equipment for some critical aircraft components, such as turbine-engine inlets, should, however, be designed for approximately the severest ice-collection rates expected. For airplanes equipped with ice-protection equipment which is designed for ice-collection rates less than the maximum expected, meteorological forecasting and navigation will have to be employed to avoid the extreme 2279
conditions; or the aircraft will have to be operated on the assumption that the ice-protection equipment for the noncritical components can be overloaded for a short time until the aircraft emerges into clear air or less severe conditions.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 27, 1951

REFERENCES

1. Kline, Dwight B.: Investigation of Meteorological Conditions Associated with Aircraft Icing in Layer-Type Clouds for 1947-48 Winter. NACA TN 1793, 1949.

2. Lewis, William, and Hoecker, Walter H., Jr.: Observations of Icing Conditions Encountered in Flight During 1948. NACA TN 1904, 1949.

3. Lewis, William, Kline, Dwight B., and Steinmetz, Charles P.: A Further Investigation of the Meteorological Conditions Conducive to Aircraft Icing. NACA TN 1424, 1947.

4. Kline, Dwight B., and Walker, Joseph A.: Meteorological Analysis of Icing Conditions Encountered in Low-Altitude Stratiform Clouds. NACA TN 2306, 1951.

5. Lewis, William: A Flight Investigation of the Meteorological Conditions Conducive to the Formation of Ice on Airplanes. NACA TN 1393, 1947.

6. Orr, John L., Fraser, D., and Pettit, K. G.: Canadian Experiments on Artificially Inducing Precipitation. Bull. Am. Meteorological Soc., vol. 31, no. 2, Feb. 1950, pp. 56-59.

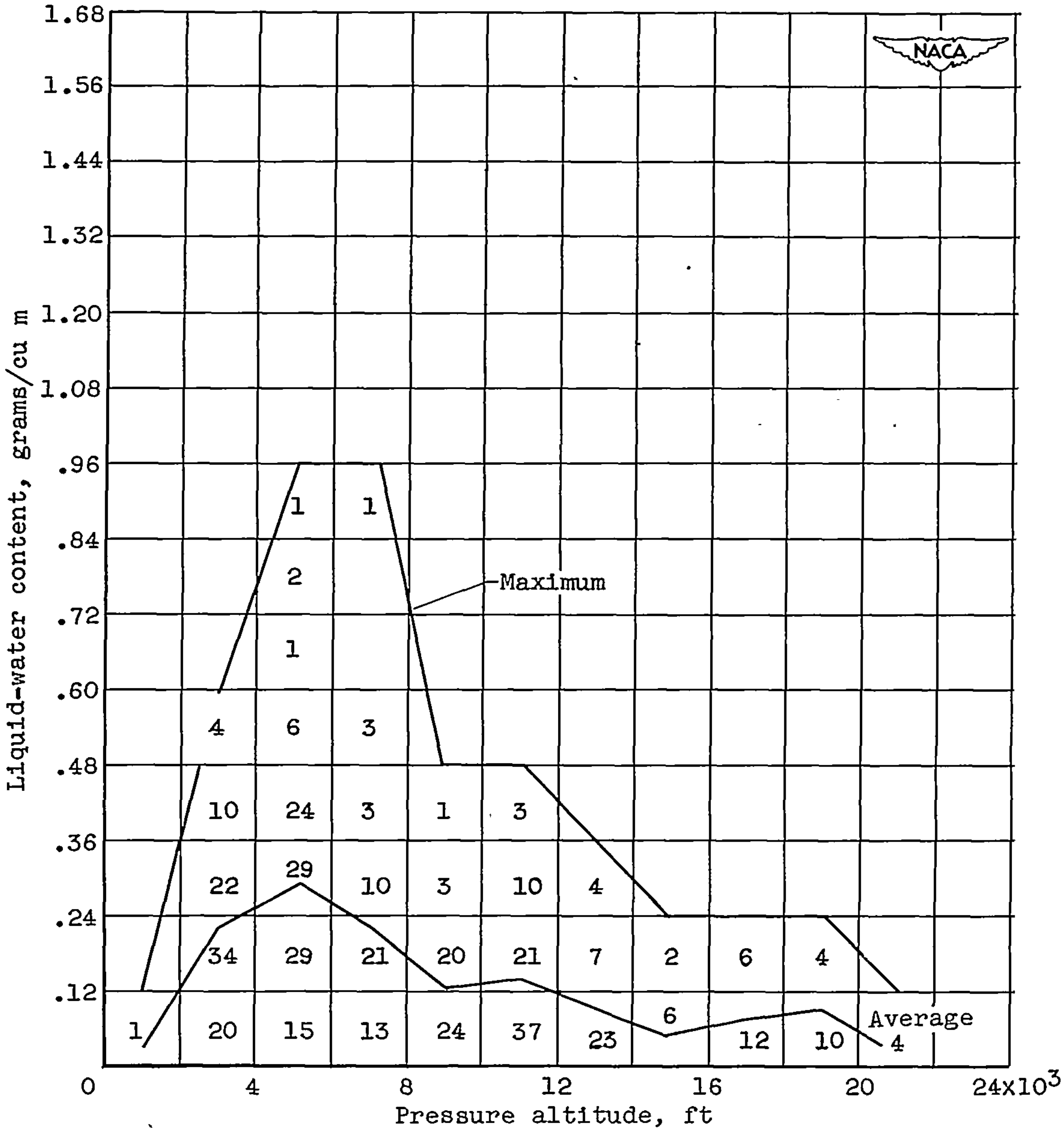
7. Anon.: The Multicylinder Method. The Mount Washington Monthly Res. Bull., vol. II, no. 6, June 1946.

8. Langmuir, Irving, and Blodgett, Katherine B.: A Mathematical Investigation of Water Droplet Trajectories. Tech. Rep. No. 5418, Air Materiel Command, AAF, Feb. 19, 1946. (Contract No. W-33-038-ac-9151 with Gen. Elec. Co.)

9. Peppler, Wilhelm: Supercooled Water - and Ice Clouds. Abs. in Bull. Am. Meteorological Soc., vol. 29, no. 9, Nov. 1948, p. 458.

10. Anon.: The Thunderstorm. U.S. Dept. Commerce, June 1949, p. 49.

11. Guibert, A. G., Janssen, E., and Robbins, W. M.: Determination of Rate, Area, and Distribution of Impingement of Waterdrops on Various Airfoils from Trajectories Obtained on the Differential Analyzer. NACA RM 9A05, 1949.



(a) Stratiform clouds.

Figure 1. - Frequency distribution of icing observations for various increments of liquid-water content and pressure altitude. (Numbers given indicate number of icing conditions observed with these conditions.)

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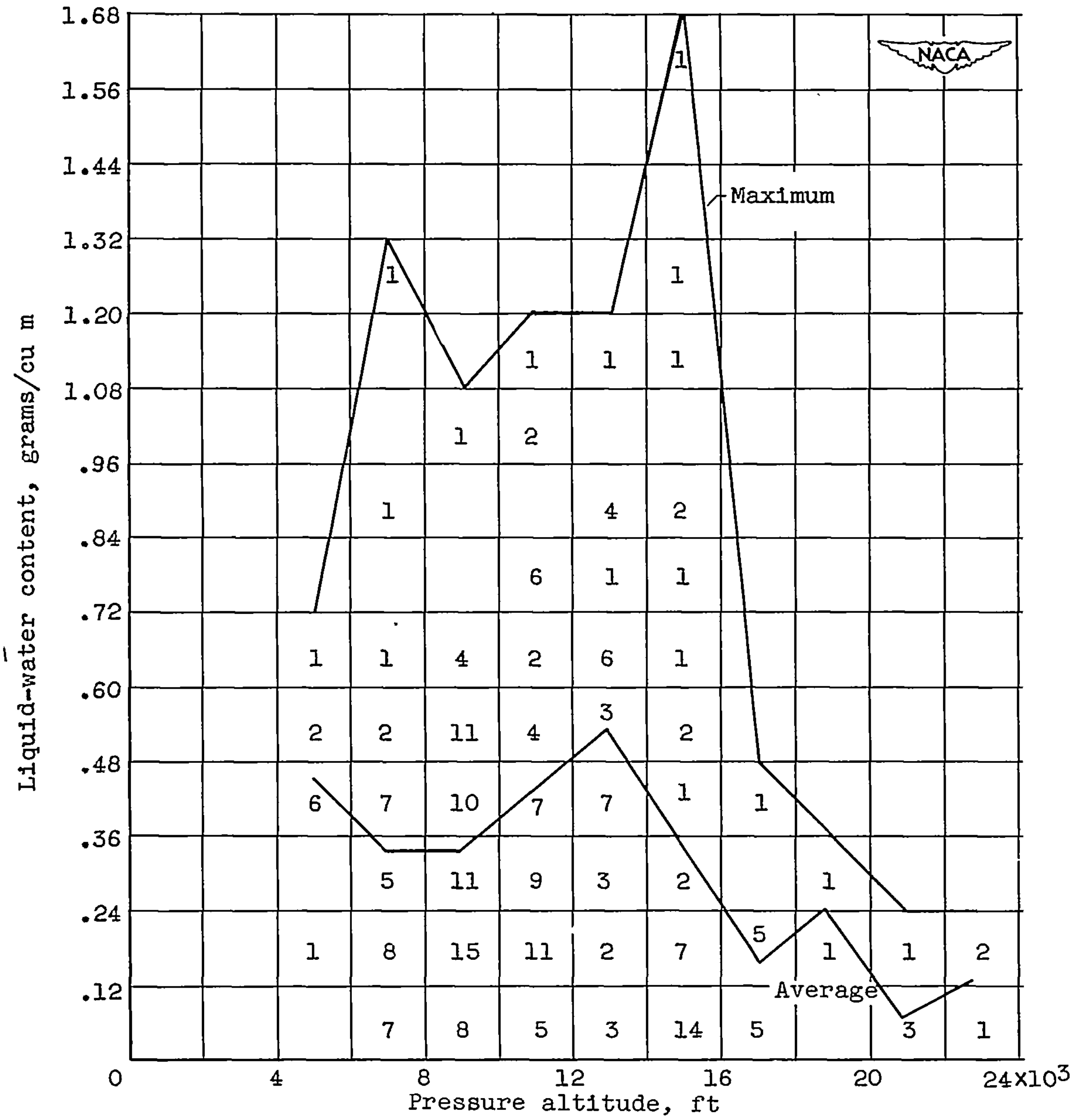
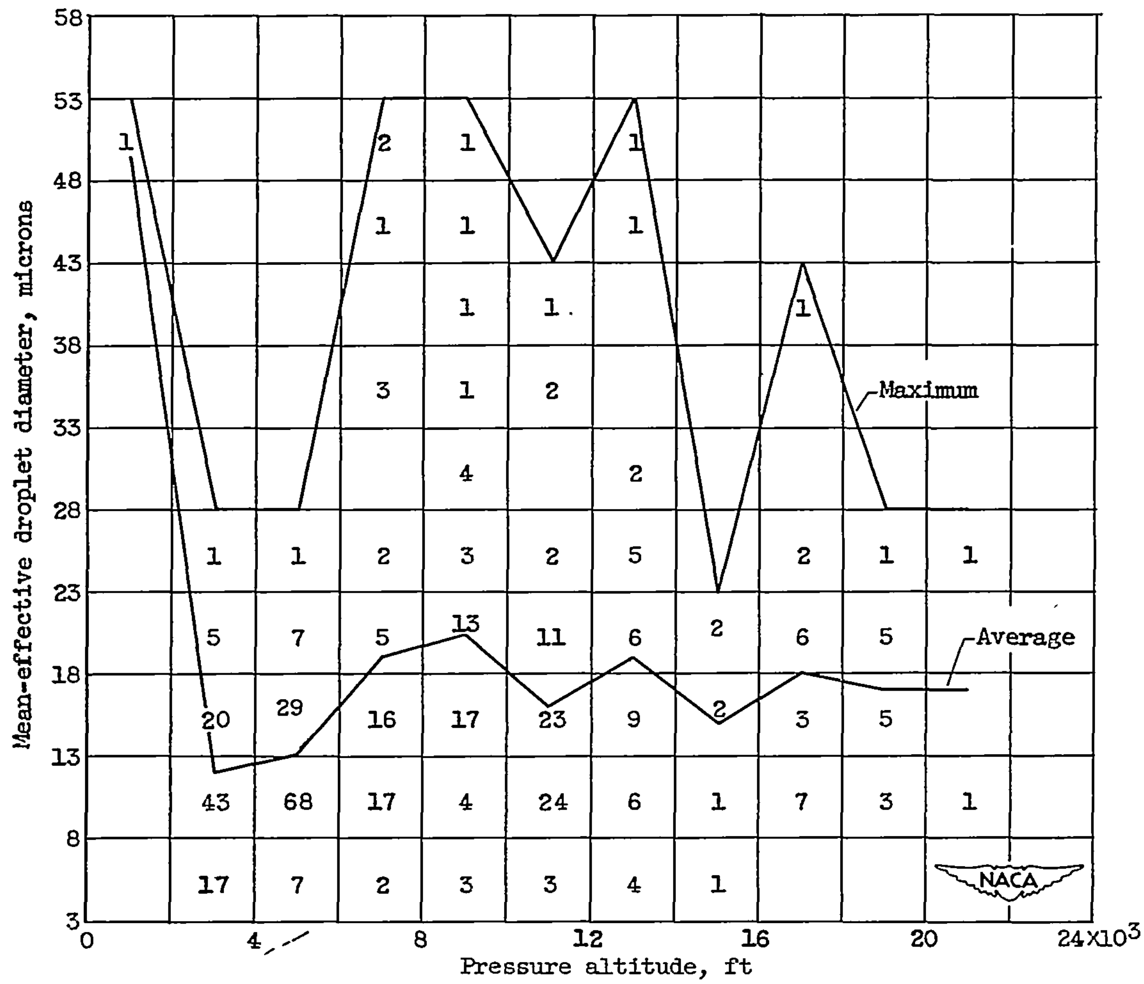


(b) Cumuliform clouds.

Figure 1. - Concluded. Frequency distribution of icing observations for various increments of liquid-water content and pressure altitude. (Numbers given indicate number of icing conditions observed with these conditions.)



(a) Stratiform clouds.

Figure 2. - Frequency distribution of icing observations for various increments of mean-effective droplet diameter and pressure altitude. (Numbers given indicate number of icing conditions observed with these conditions.)

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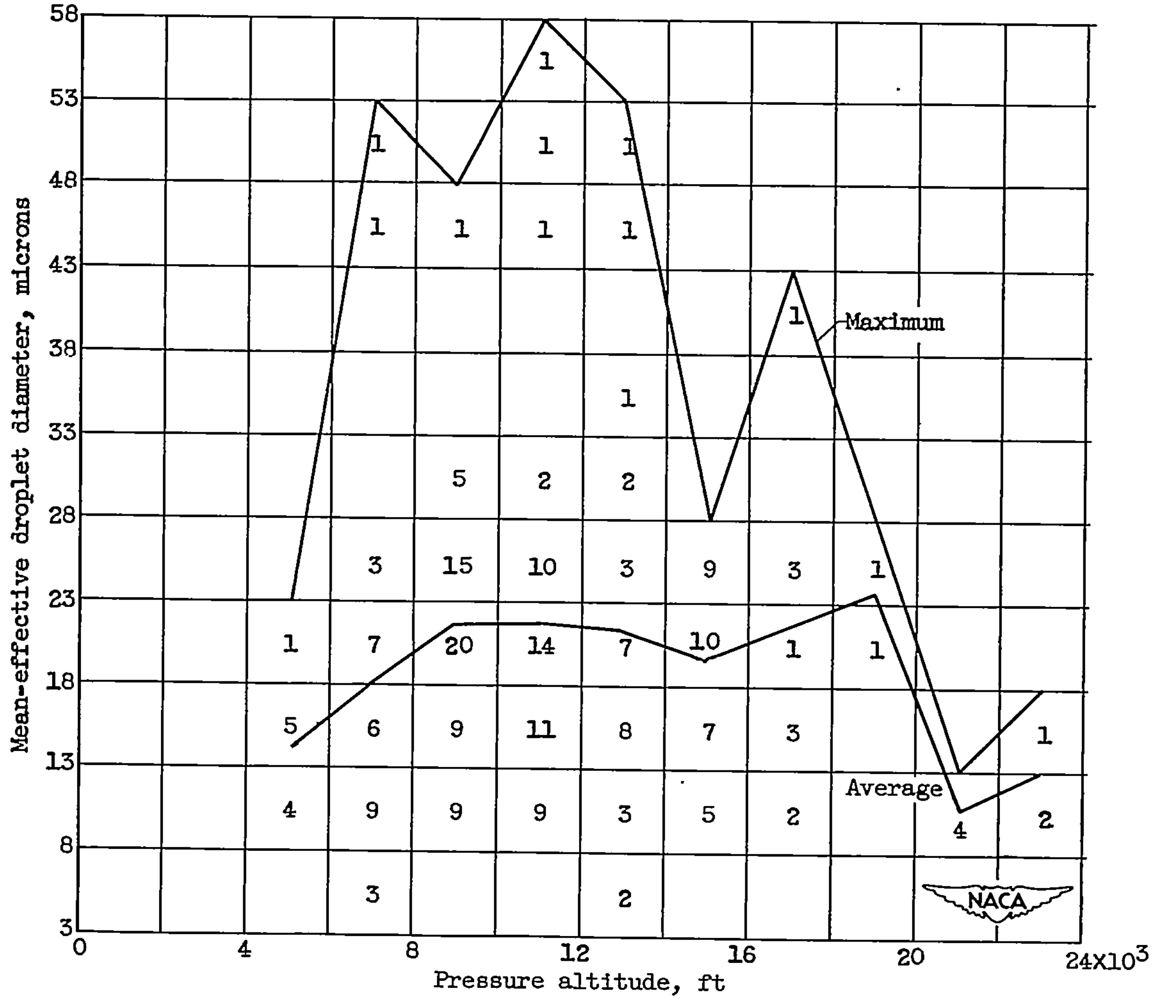
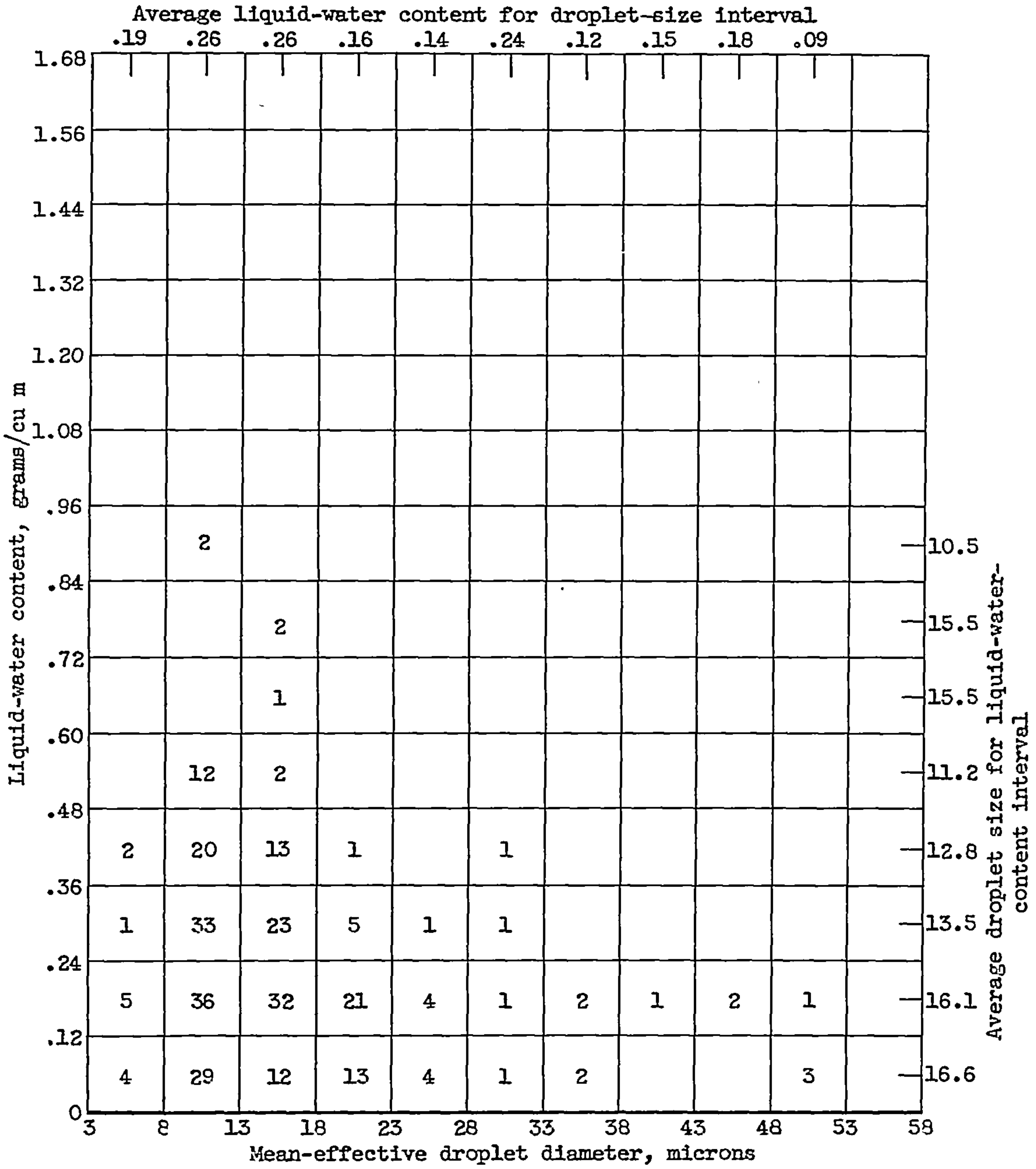


(b) Cumuliform clouds.

Figure 2. - Concluded. Frequency distribution of icing observations for various increments of mean-effective droplet diameter and pressure altitude. (Numbers given indicate number of icing conditions observed with these conditions.)



(a) Stratiform clouds between pressure altitudes of 0 and 10,000 feet.

Figure 3. - Frequency distribution of icing observations for various increments of liquid-water content and mean-effective droplet diameter. (Numbers given indicate number of icing conditions observed with these conditions.)

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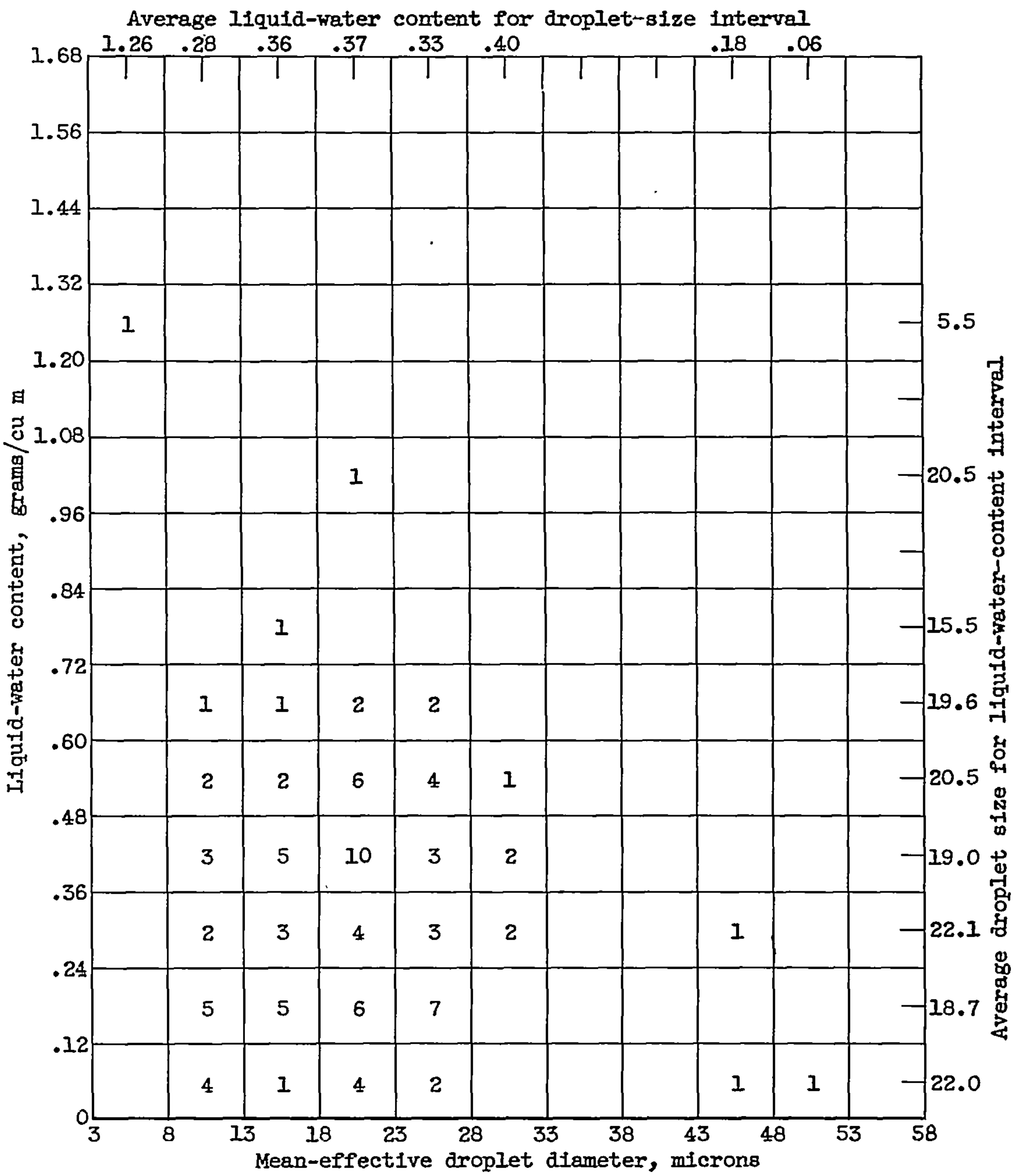

(b) Cumuliform clouds between pressure altitudes of 0 and 10,000 feet.

Figure 3. - Continued. Frequency distribution of icing observations for various increments of liquid-water content and mean-effective droplet diameter. (Numbers given indicate number of icing conditions observed with these conditions.)

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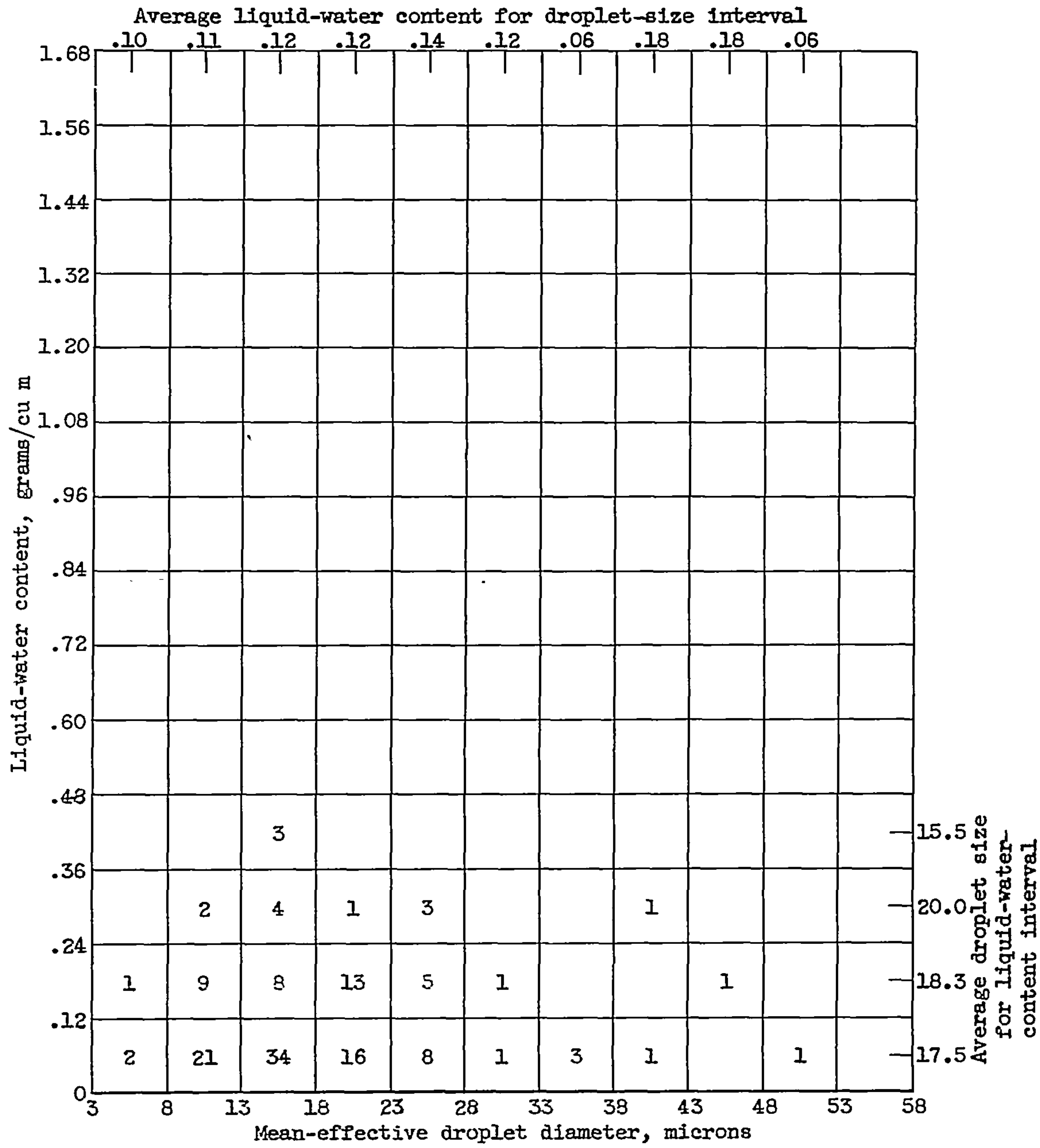
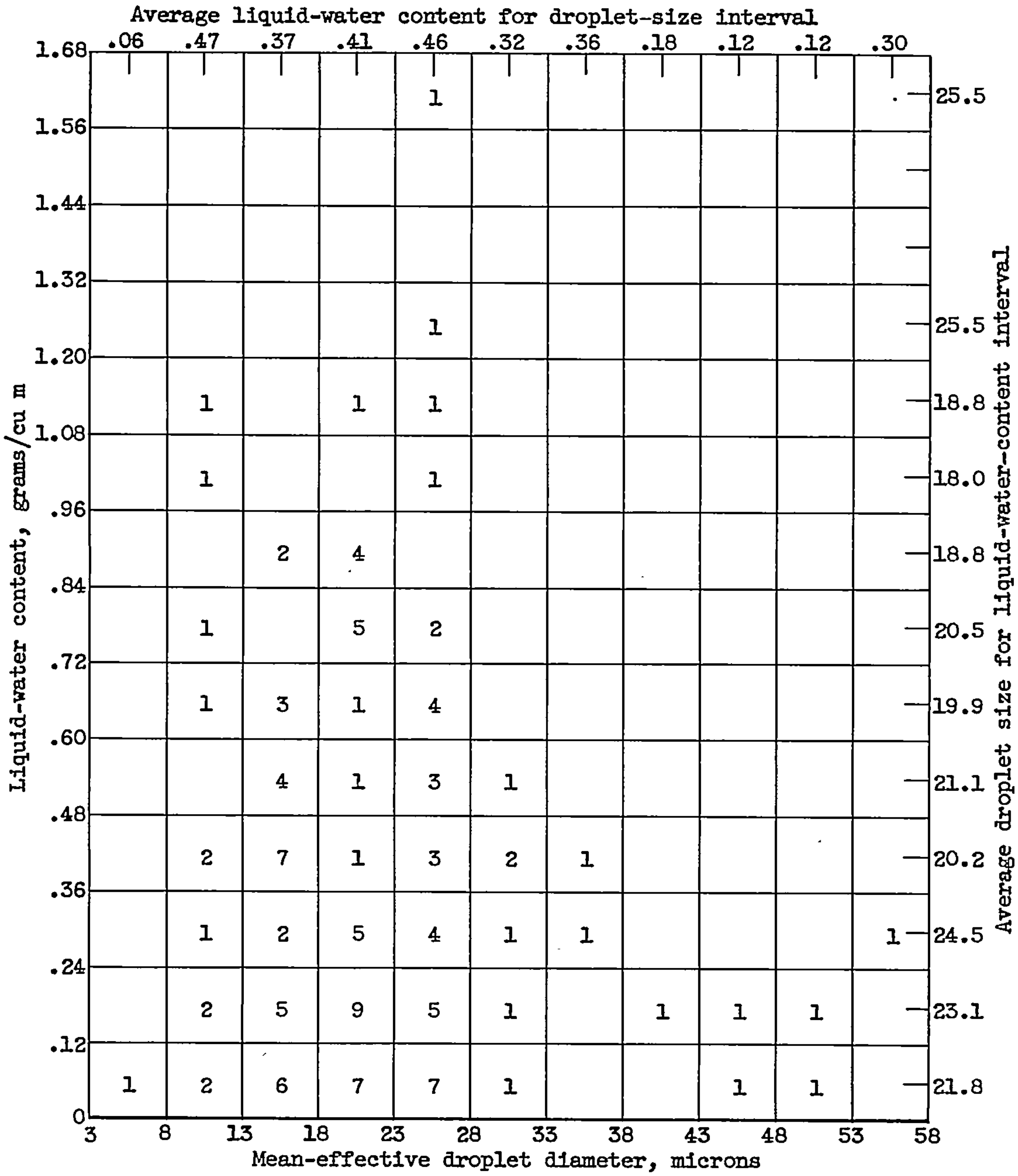


(c) Stratiform clouds between pressure altitudes of 10,000 and 20,000 feet.

Figure 3. - Continued. Frequency distribution of icing observations for various increments of liquid-water content and mean-effective droplet diameter. (Numbers given indicate number of icing conditions observed with these conditions.)



(d) Cumuliform clouds between pressure altitudes of 10,000 and 20,000 feet.

Figure 3. - Concluded. Frequency distribution of icing observations for various increments of liquid-water content and mean-effective droplet diameter. (Numbers given indicate number of icing conditions observed with these conditions.)

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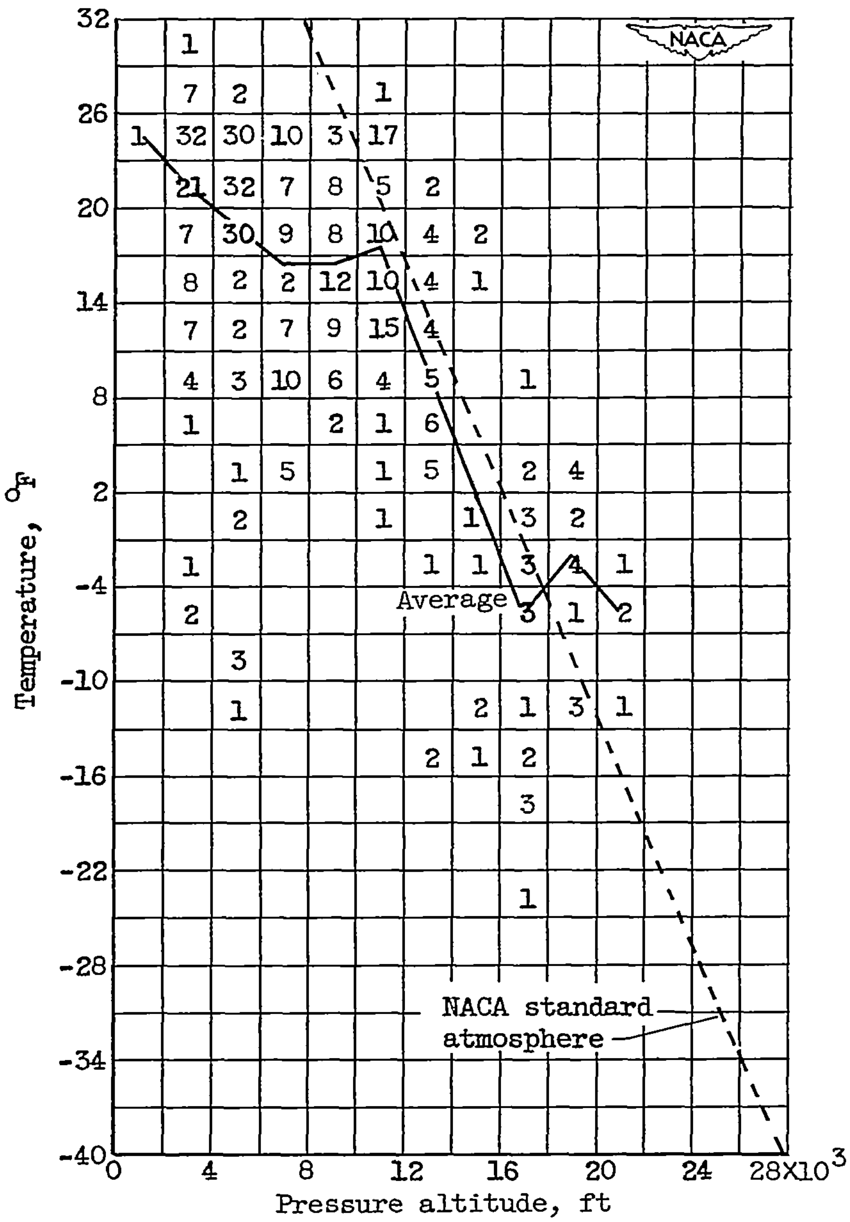

(a) Stratiform clouds.

Figure 4. - Frequency distribution of icing observations for various increments of temperature and pressure altitude. (Numbers given indicate number of icing conditions observed with these conditions.)

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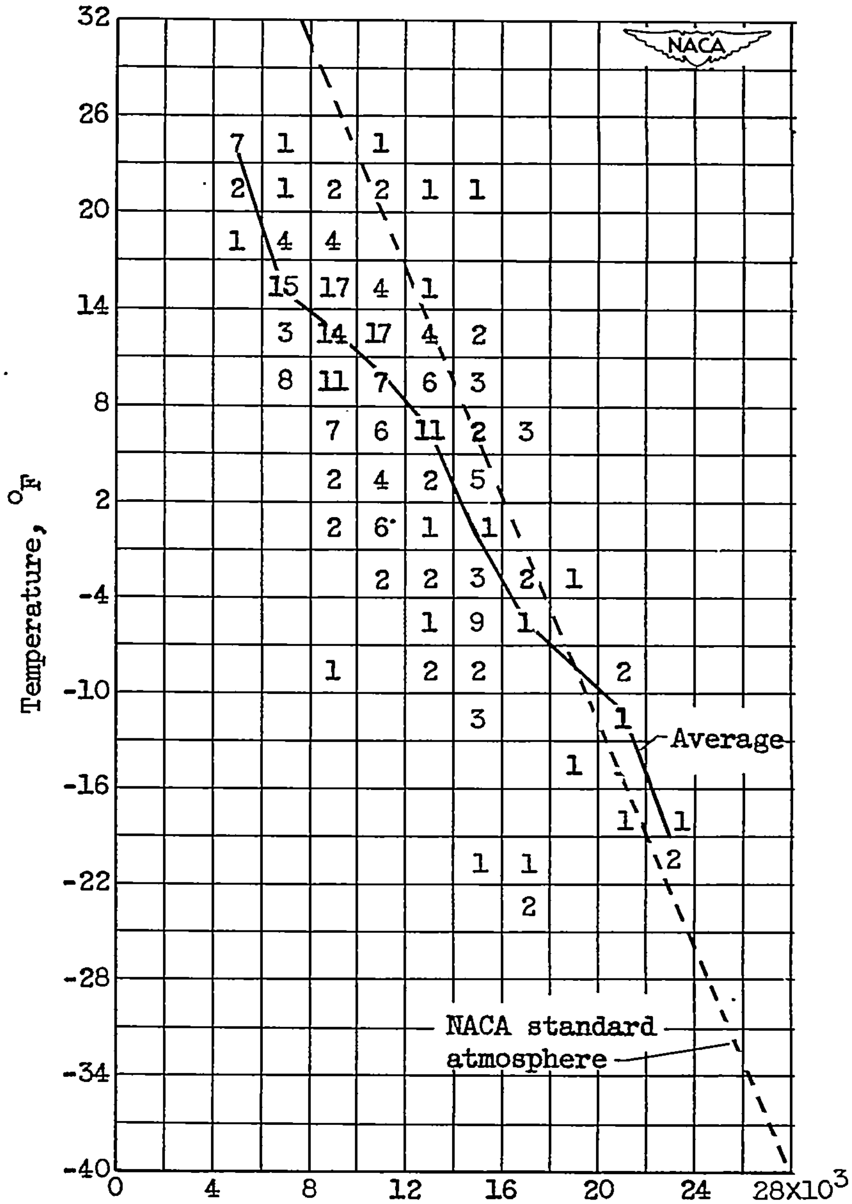

(b) Cumuliform clouds.

Figure 4. - Concluded. Frequency distribution of icing observations for various increments of temperature and pressure altitude. (Numbers given indicate number of icing conditions observed with these conditions.)

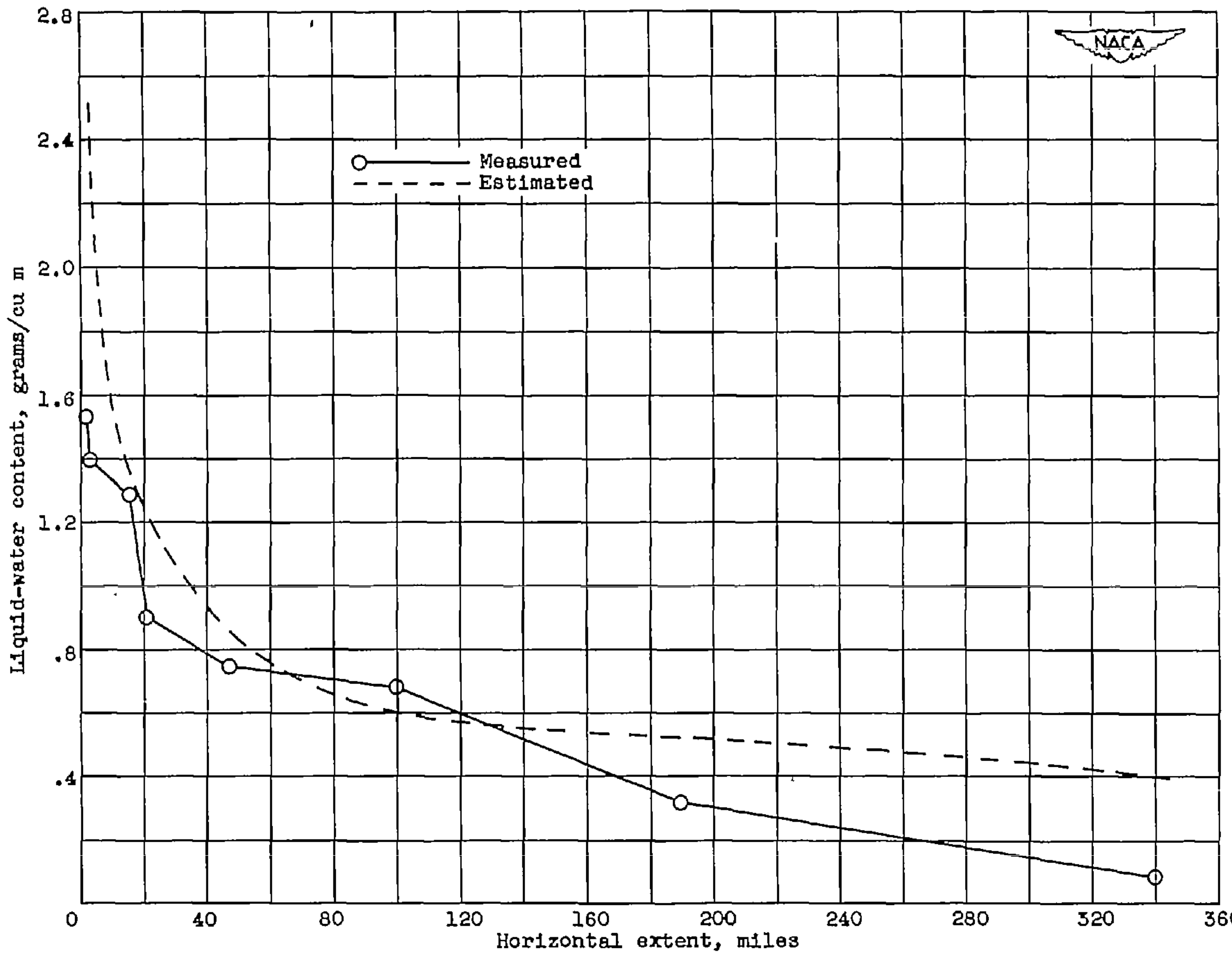

Figure 5. - Maximum horizontal extent of icing encounters in relation to average liquid-water content.

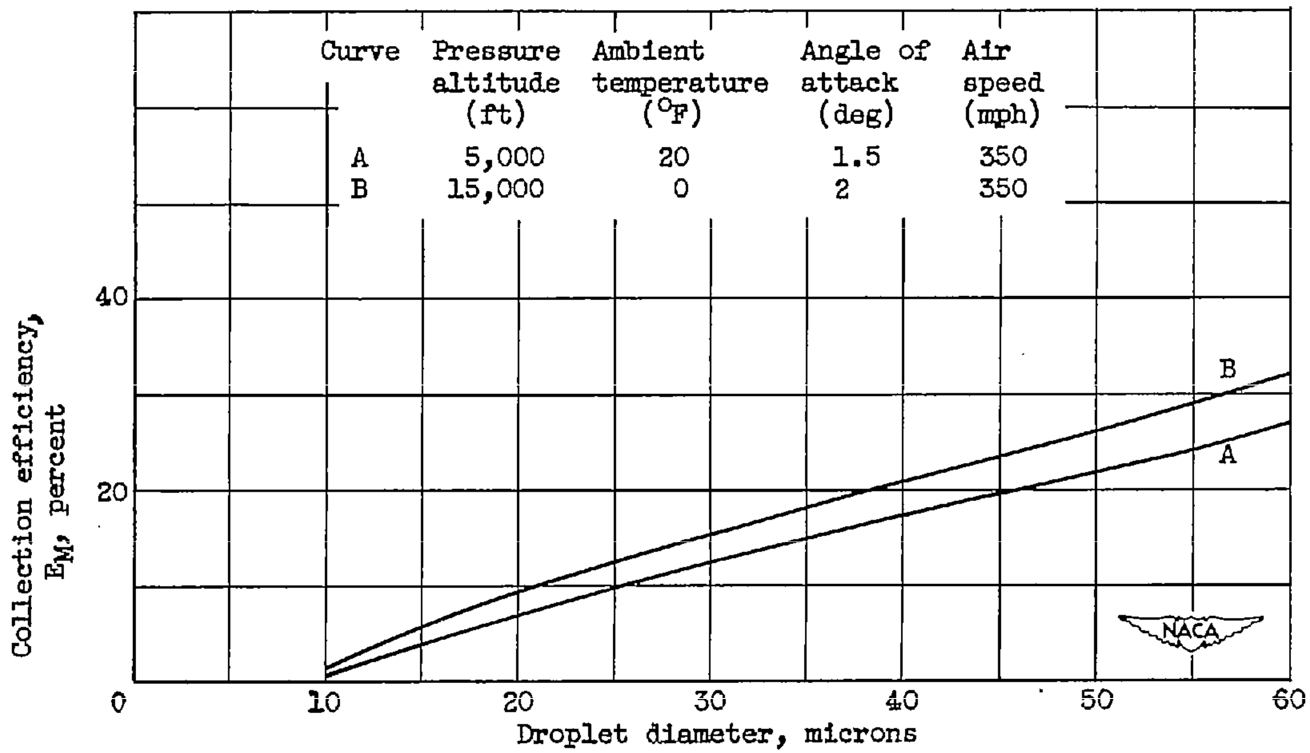

Figure 6. - Variation of collection efficiency with droplet diameter for a hypothetical, 12-percent thick, low-drag airfoil with a chord length of 15.8 feet for two altitude, temperature, and angle-of-attack conditions.

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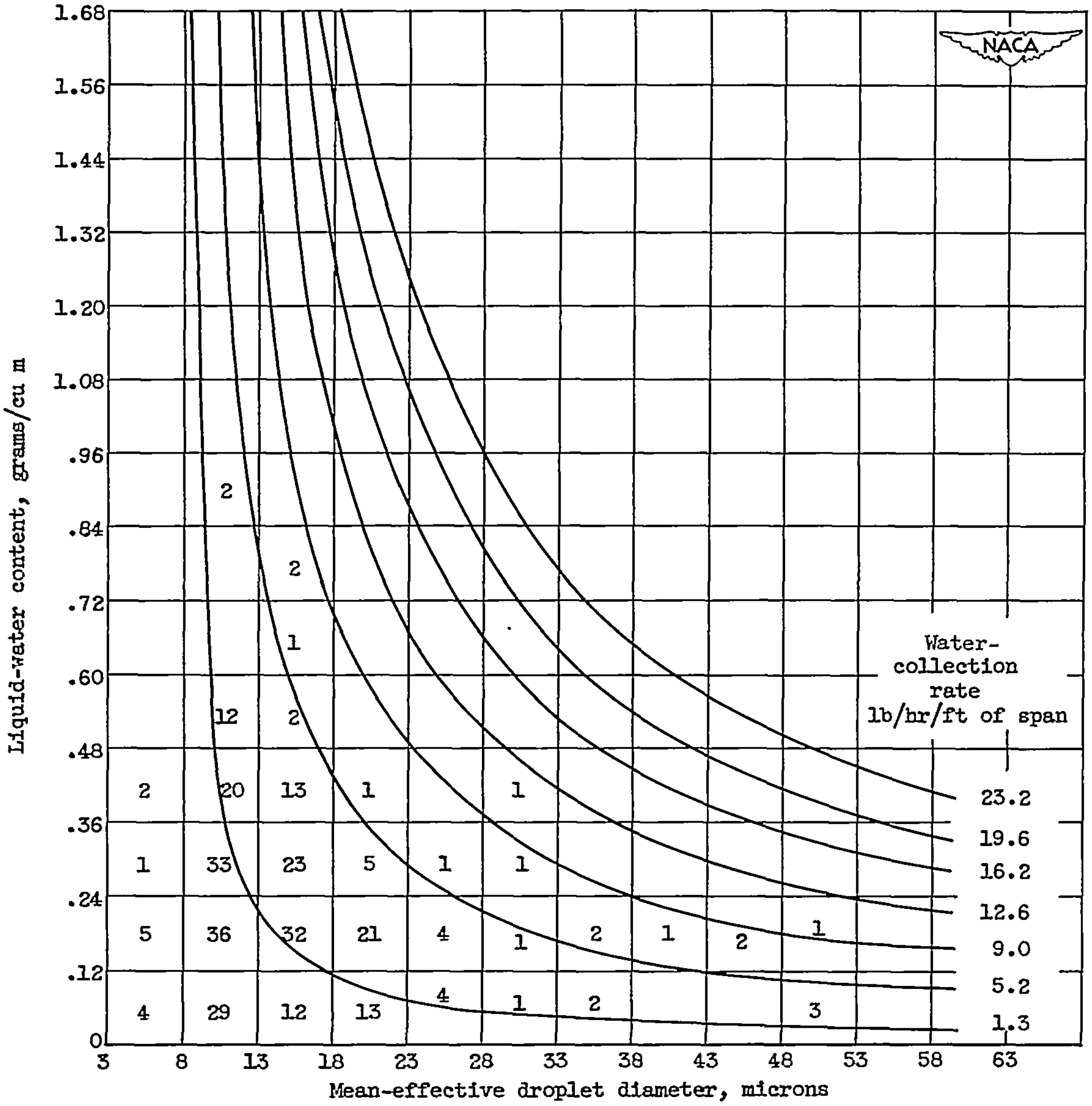

(a) Stratiform clouds between pressure altitudes of 0 and 10,000 feet. (Based on curve A of fig. 6, and fig. 3(a)).

Figure 7. - Constant water-collection-rate curves for hypothetical airfoil superimposed on frequency distribution of icing observations.

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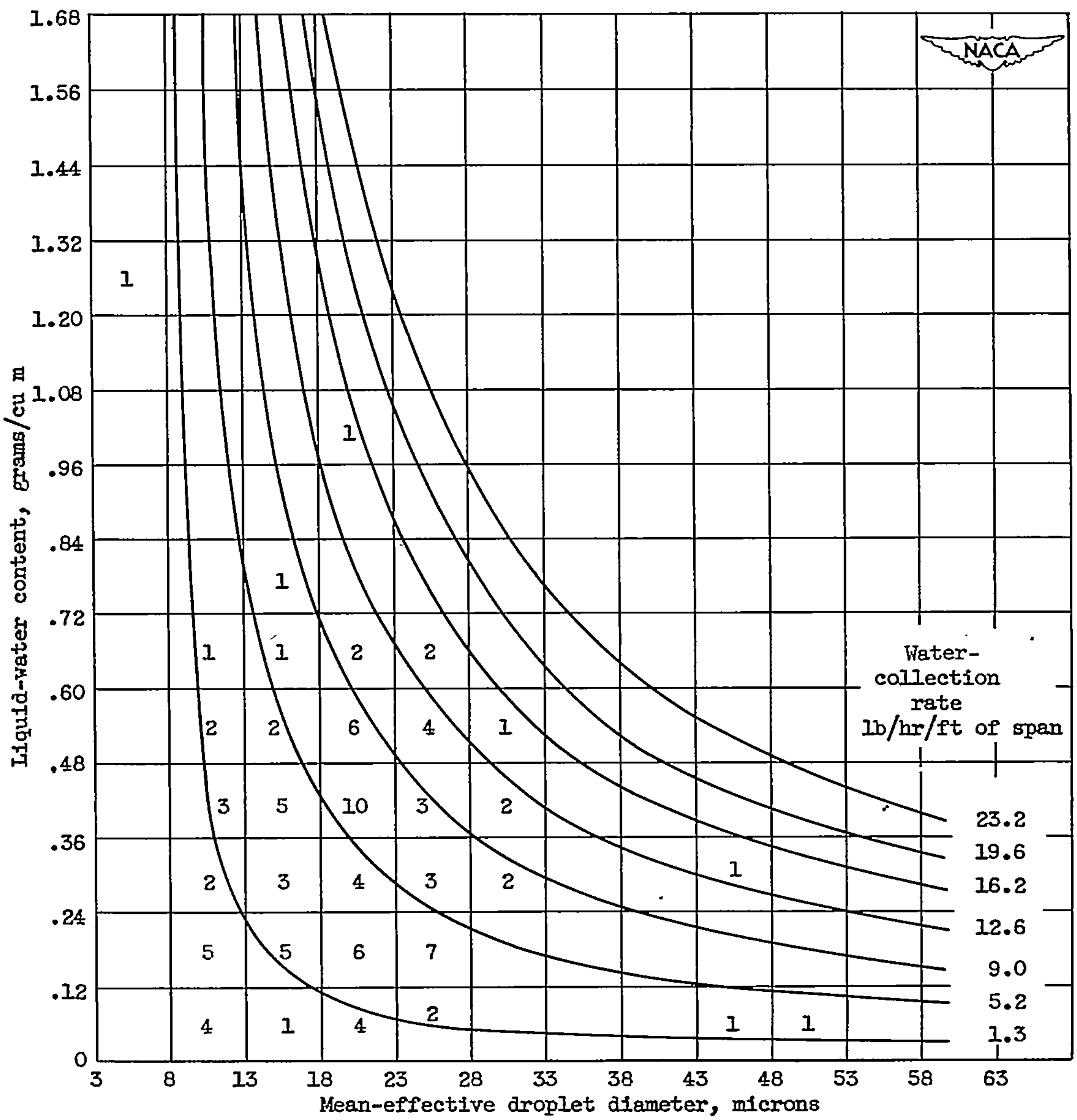
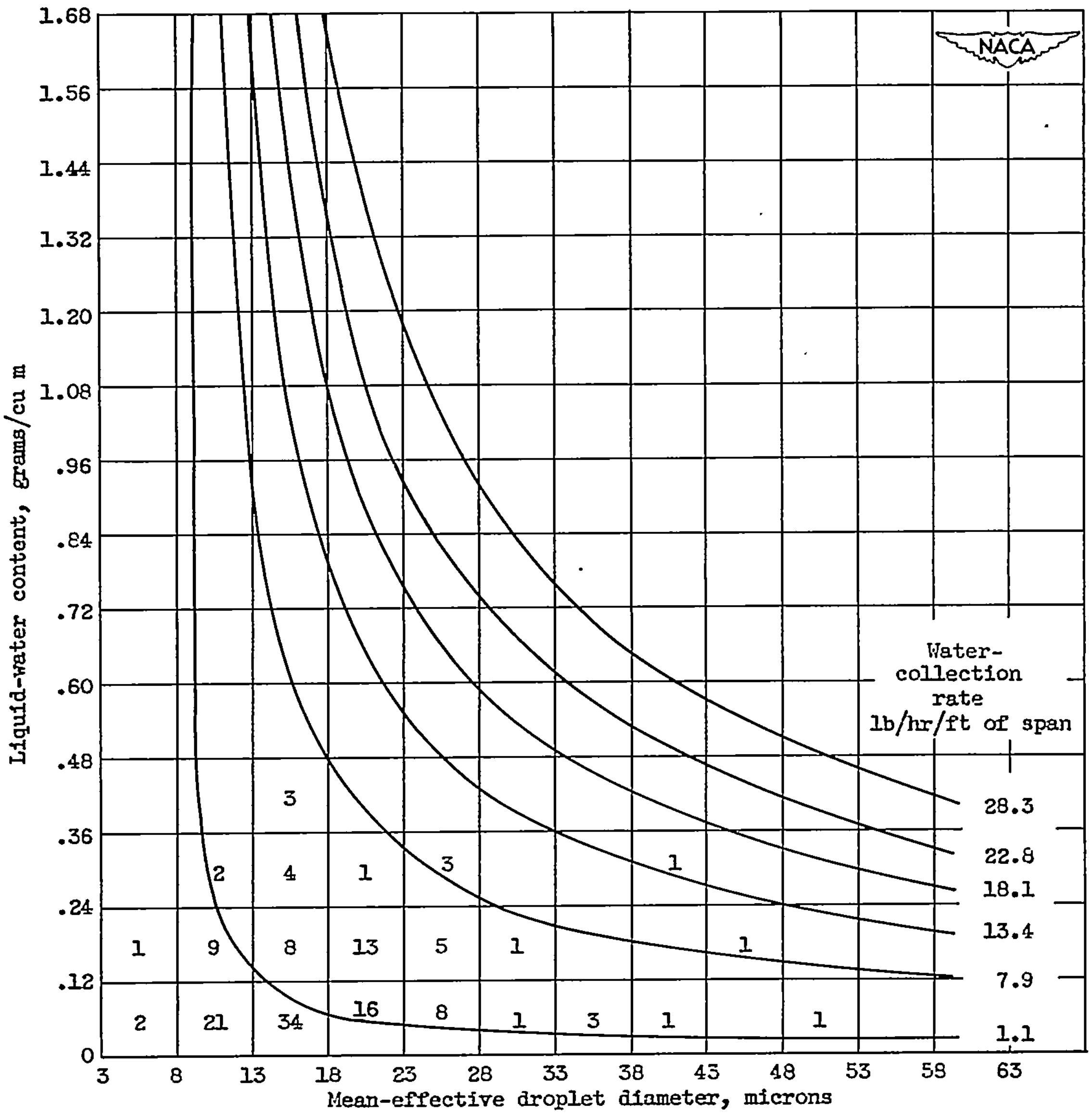


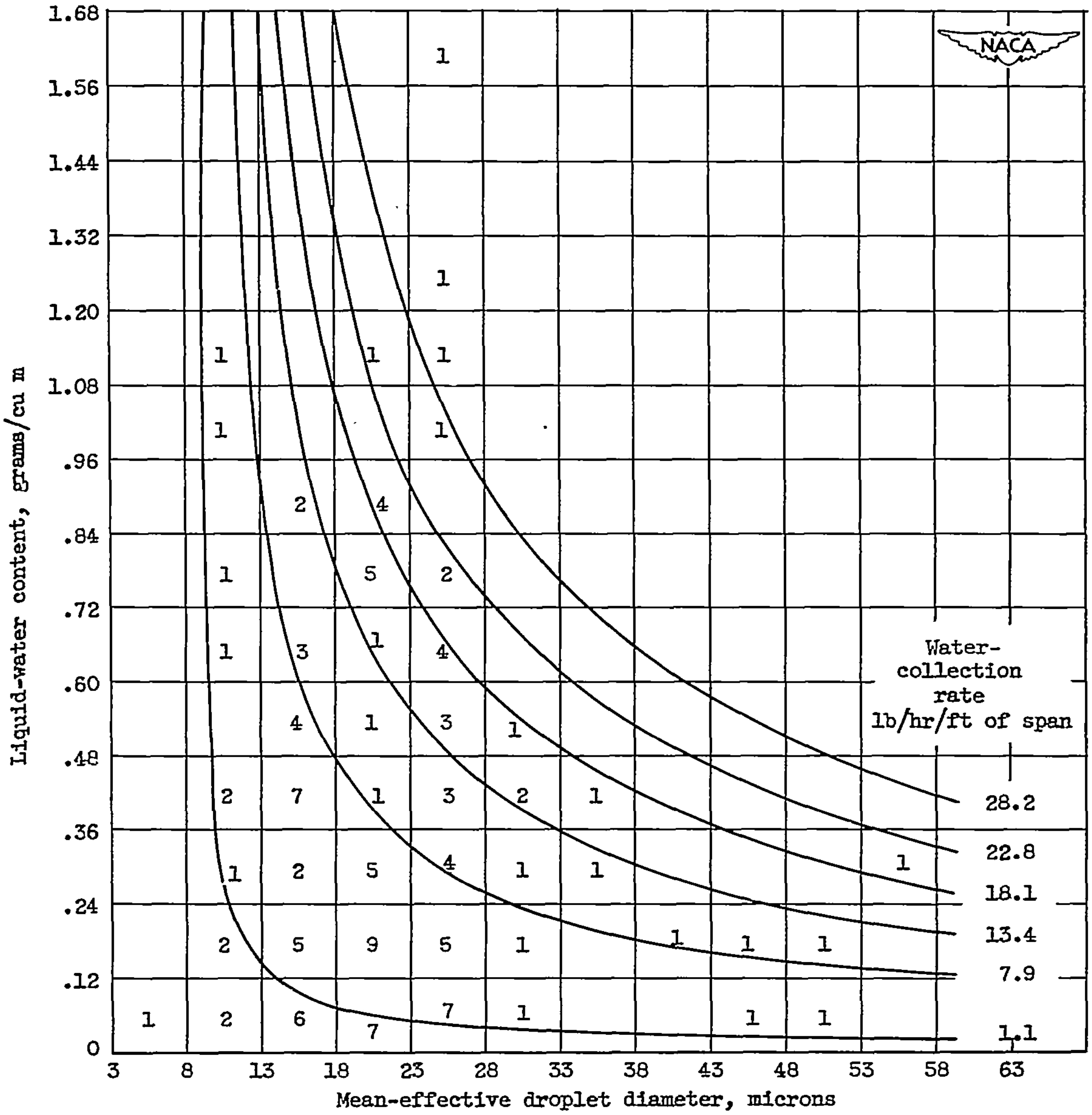
(b) Cumuliform clouds between pressure altitudes of 0 and 10,000 feet. (Based on curve A of fig. 6, and fig. 3(b)).

Figure 7. - Continued. Constant water-collection-rate curves for hypothetical airfoil superimposed on frequency distribution of icing observations.



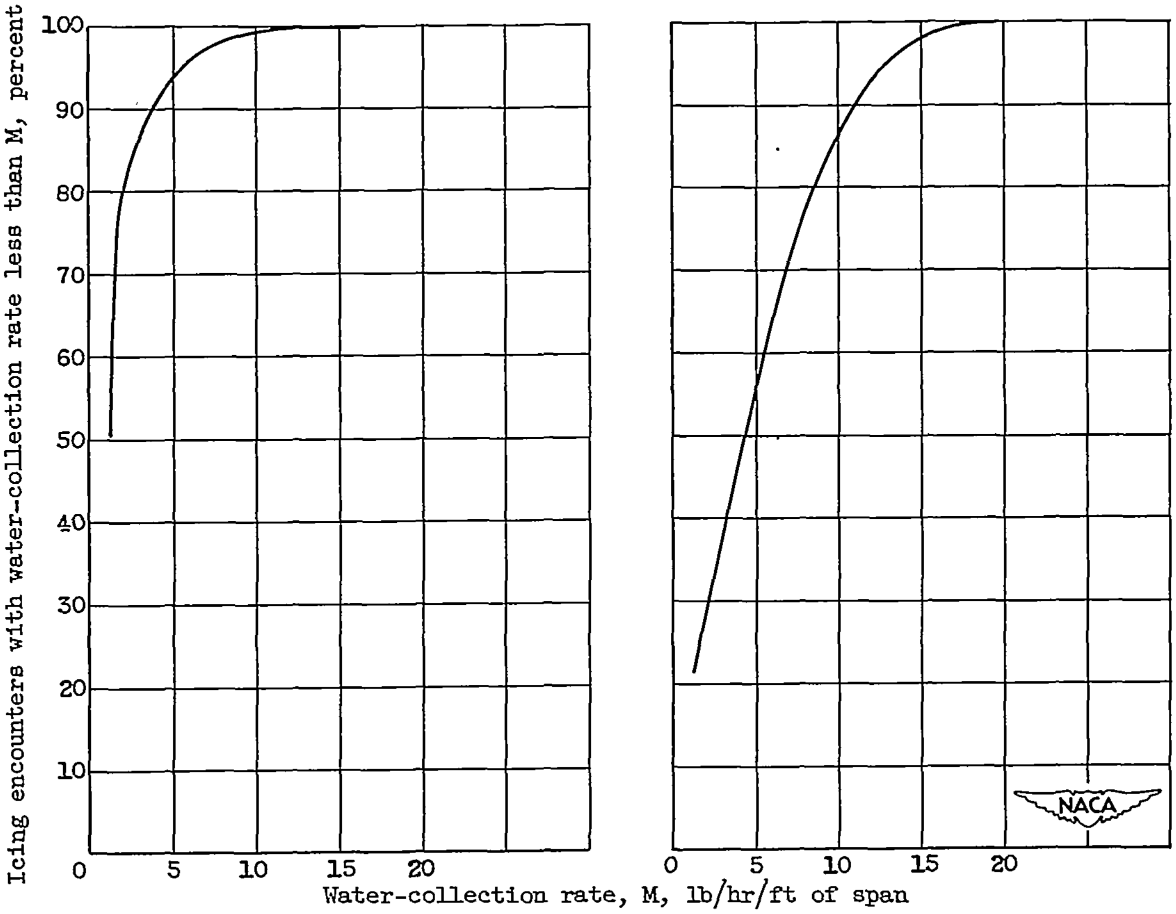
(c) Stratiform clouds between pressure altitudes of 10,000 and 20,000 feet. (Based on curve B of fig. 6, and fig. 3(c)).

Figure 7. - Continued. Constant water-collection-rate curves for hypothetical airfoil superimposed on frequency distribution of icing observations.



(d) Cumuliform clouds between pressure altitudes of 10,000 and 20,000 feet. (Based on curve B of fig. 6, and fig. 3(d)).

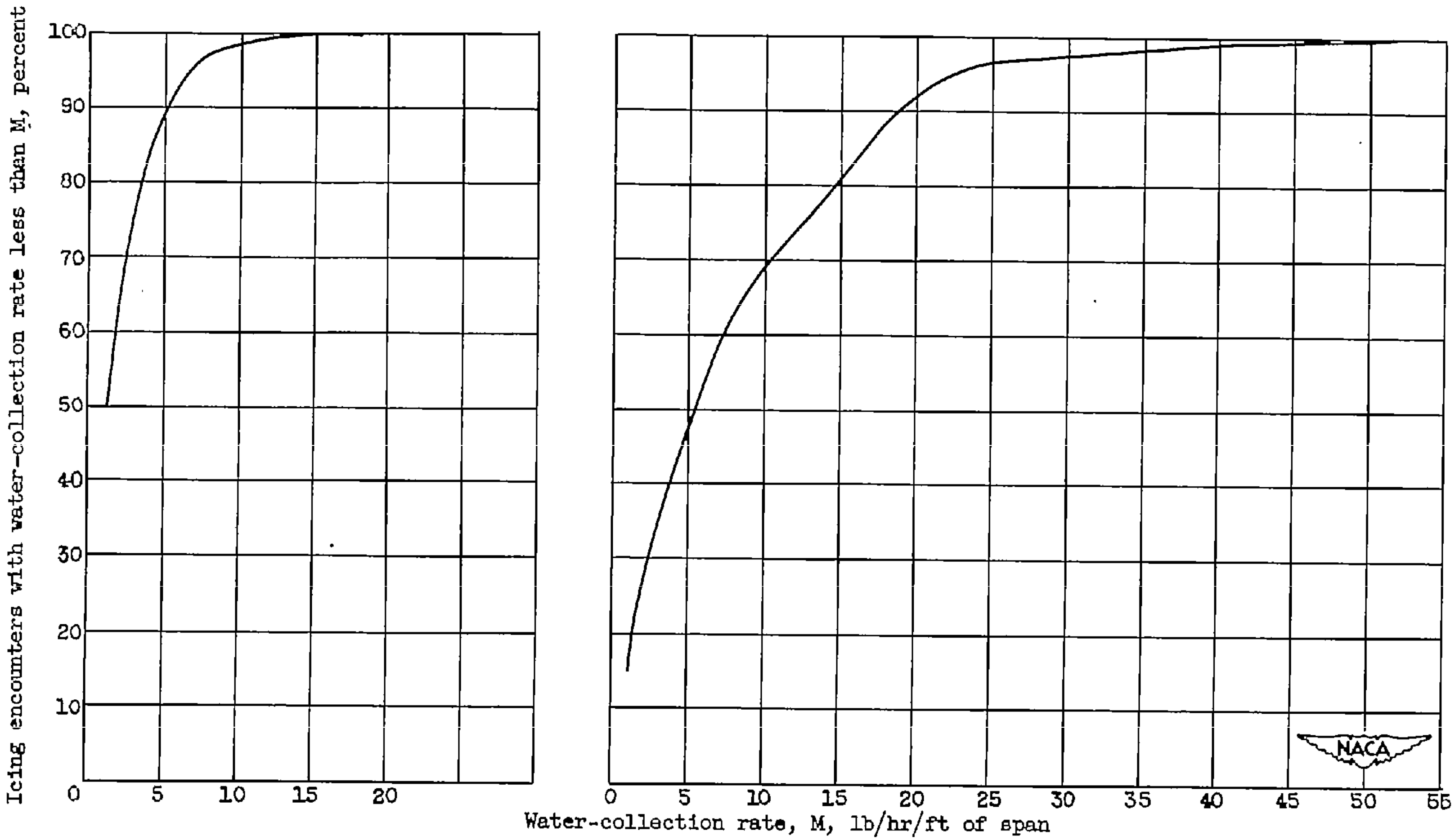
Figure 7. - Concluded. Constant water-collection-rate curves for hypothetical airfoil superimposed on frequency distribution of icing observations.



(a) Stratiform clouds; pressure altitude, 0 to 10,000 feet; airfoil angle of attack, 1.5°.

(b) Cumuliform clouds; pressure altitude, 0 to 10,000 feet; airfoil angle of attack, 1.5°.

Figure 8. - Frequency curves of rate of water collection for a hypothetical, 12-percent thick, low-drag airfoil with a chord length of 15.8 feet and airspeed of 350 miles per hour.



(c) Stratiform clouds; pressure altitude, 10,000 to 20,000 feet; airfoil angle of attack, 2°.

(d) Cumuliform clouds; pressure altitude, 10,000 to 20,000 feet; airfoil angle of attack, 2°.

Figure 8. - Concluded. Frequency curves of rate of water collection for a hypothetical, 12-percent thick, low-drag airfoil with a chord length of 15.8 feet and airspeed of 350 miles per hour.